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Tropical Cyclone Signals within Tree-Ring Chronologies from Weeks Bay National Estuary and Research Reserve, Alabama

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ABSTRACT

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This study investigates the relationship between tropical cyclones and tree-ring chronologies within a bottomland forest in coastal Alabama. Tree cores were collected from 36 slash pines in the Swift Track area of the Weeks Bay National Estuary and Research Reserve, Fairhope, Alabama. Tree cores were processed, measured to the nearest 0.01 mm, and cross-dated using standard procedures. A standardized ring index series was computed from the tree-ring measurement for each year from 1890 to 2000. The index series represents a single chronology of the entire forest stand, which we refer to as the stand-scale. An initial comparison of index series values to years of known tropical storm and hurricane strikes within the Weeks Bay area reveals no clear tropical cyclone signal. Statistical tests of the index values for 2–7 y periods before and after tropical storms and hurricanes indicate no statistically significant difference in tree-rings before and after the storms. In contrast, standardized index values computed for each individual tree-ring series (individual tree-scale) display more rapid growth (release) in years following direct hits by tropical cyclones. Individual tree-ring data also indicate slowed growth (suppression) during years when tropical cyclones are infrequent. These results indicate that researchers must be aware of scale of analysis when researching tree-ring chronologies in Gulf Coast forests. For this study, a combination of the two scales of analysis results in a recognizable tree-ring record of suppression and then release generated by tropical cyclones.

ADDITIONAL INDEX WORDS: *Tree-ring analysis, hurricanes, Weeks Bay, Alabama.*

INTRODUCTION

Hurricanes are a major natural disturbance agent within forest ecosystems of North America. Specific documentation of hurricane disturbances have been reported in the Northeast (BORMANN and LIKENS, 1979; COOPER-ELLIS *et al.,* 1999; OLIVER, 1981), southern Appalachia (ELLIOTT *et al.,* 2002; GREENBERG and MCNAB, 1998), and the U.S. southeastern Coastal Plain (CONNER *et al.,* 1998; MYERS and VAN LEAR, 1998; PLATT *et al.,* 2002; PUTZ and SHARITZ, 1991; SHARITZ *et al.,* 1993). Hurricanes have also been reported to affect forests in the Neotropics (BOUCHER, 1990; ROSS *et al.,* 2001; VANDERMEER *et al.,* 2000). In all of these locations, the physical damage associated with landfalling hurricanes caused widespread tree mortality, which subsequently altered many forest ecosystem processes.

The physical damage to forests from hurricanes is generally related to high-velocity winds and/or flooding. High-velocity winds, whether from the actual hurricane or from tornadoes spawned during the hurricane, can uproot trees, snap tree trunks, break off stems, and rip off leaves (FRANCIS and GILLESPIE, 1993). Flooding, whether from freshwater precipitation or from saline storm surge, severely stresses tree roots from the lack of oxygen and/or from saline conditions (CONNER *et al.,* 1998). Ultimately, these stressors can lead to tree mortality. The effects of both types of damage may alter species composition and structure, redirect ecological succession, change species diversity, and interfere with nutrient cycling (BATTAGLIA *et al.*, 1999; BOUCHER, 1990; COOPER-ELLIS *et al.*, 1999; ELLIOT *et al.,* 2002; MYERS and VAN LEAR, 1998).

Despite multiple studies indicating that hurricanes play an important role in coastal forest dynamics, uncertainties still exist in regard to the exact function of hurricanes within disturbance ecology and the specific responses of ecosystems to hurricane damage (COOPER-ELLIS *et al.,* 1999; MYERS and VAN LEAR, 1998). This is especially true for the central and eastern Gulf Coast of North America (Alabama, Florida, and eastern Mississippi), where few studies of modern hurricane disturbance have been completed. Research has been completed within this region regarding the paleoclimatology of hurricanes (LIU and FEARN, 1993). Sediment records in coastal Alabama indicate that hurricanes have occurred throughout the Holocene (the last 10,000 y), several of which

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appear to have been category 3 and category 4 in magnitude (LIU and FEARN, 1993). Further, it appears that cyclones of this magnitude have a reoccurrence interval of approximately once every 600 y (LIU and FEARN, 1993). Thus, given this paleoclimatic record, the potential impact of hurricanes upon the coastal forests of the central Gulf Coast may exist but has yet to be documented within recent time periods.

One method that may help elucidate modern forest responses to hurricanes in the central Gulf Coast is tree-ring analysis. The destructive force of tropical cyclones, whether from high winds or flooding, will greatly stress and impede tree growth and thus, extreme stress may be evident within the annual growth rings. For example, trees within the path of Hurricane Camille (1969) in Louisiana and Mississippi had narrow or missing rings in the years that immediately followed the storm, and they showed suppressed growth for up to 3 to 7 y after that landfall event (DOYLE and GORHAM, 1996). Additionally, along the Louisiana and Mississippi coasts, research has shown that years of known hurricane strikes correspond to the most influential data points within a regression model of tree-ring width and annual moisture (REAMS and VAN DEUSEN, 1996).

These studies suggest that tree-ring records in the western portion of the Gulf Coast are sensitive to hurricanes and that they can be used to potentially provide a long-term record of hurricane effects on coastal forests in the understudied central portion of the Gulf Coast. Another benefit that tree-ring analysis may offer is that it allows for the examination of two different scales of response in coastal forests to hurricanes—the broader-scale change in entire forest stands and the narrower-scale of change in individual tree growth. By using tree-ring analysis in the central Gulf Coast, a more accurate assessment of multiscale coastal forest ecosystem response to hurricane damage can be determined for a previously understudied region.

The goal of this paper is to investigate the role of tropical cyclones on an old-growth, bottomland forest in the central Gulf Coast of North America as represented by the Swift Track area of the Weeks Bay National Estuary and Research Reserve. Specifically, three hypotheses have been designed to address both stand and individual tree scale processes, in order to further our understanding of coastal forest ecosystems on multiple scales. The first hypothesis states that tropical cyclone occurrences in the Weeks Bay area will cause a decrease in tree-ring width in a master tree-ring chronology. The decrease in tree-rings might represent slowed growth due to physical tree damage caused by tropical cyclone winds and flooding. The second hypothesis states that analysis of the link between climatic variables (precipitation, temperature, and drought) and the tree-ring series for the Swift Track will further illustrate the impact of hurricanes upon this coastal forest. Since tropical cyclones have a large impact upon monthly and annual precipitation and soil moisture, these variables should reflect and reinforce existing relationships between tropical cyclones and annual tree-ring width. The third hypothesis addresses individual tree response to hurricanes, and it states that patterns of increased growth (release years) and patterns of suppressed growth (suppression years) will be directly linked to the frequency of tropical

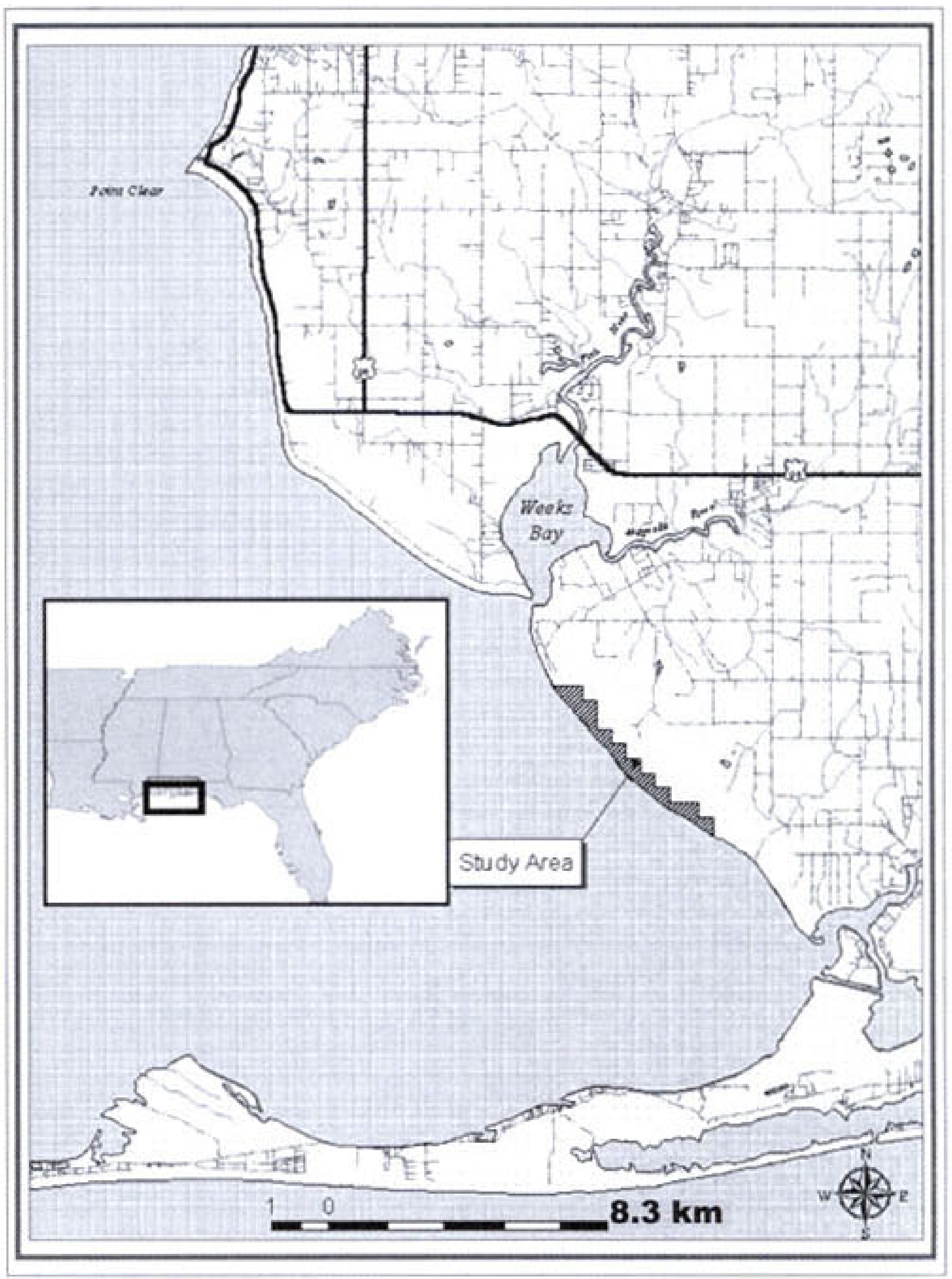

Figure 1. Location of the Swift Track study area on Mobile Bay, Alabama. The study area is managed by the Weeks Bay National Estuary Research Reserve, Fairhope, Alabama.

cyclones in the Weeks Bay area. Following the intermediate disturbance hypothesis (CONNELL, 1978), we would expect that during instances in which tropical cyclones are very frequent, trees will experience suppressed growth from the repetition of physical damage. Periods during which tropical cyclones are infrequent will also lead to suppressed growth because of increased intraspecific competition, crowding, and closure of the canopy. Moreover, by quantifying the nature of the relationship between tropical cyclone activity and release and suppression, we should be able to predict future responses of trees to tropical cyclone damage.

STUDY AREA

Weeks Bay is located on the eastern shore of Mobile Bay in Baldwin County Alabama (Figure 1). The bay is a shallow estuary (average depth 1.5 m) that receives fresh water from both the Magnolia River and the Fish River. The bay and the majority of the land directly surrounding it are managed as a National Estuary and Research Reserve (NERR) that is administered jointly by the Alabama Department of Natural Resources and National Oceanographic and Atmospheric Administration (NOAA). The NERR consists of approximately 2428 ha of water, including Weeks Bay, the Magnolia River, the Fish River, a small portion of Mobile Bay, and over 647 ha of wetland forest, swamps, and upland forest that fringe Weeks and Mobile Bay (WEEKS BAY NERR, 2005).

A portion of the Weeks Bay NERR is a narrow stretch of forest called the "Swift Track," which is located just southeast of the mouth of Weeks Bay (Figure 1). The Swift Track is a flat, bottomland forest that is flooded periodically throughout the year. It contains many large and relatively old slash pines (*Pinus elliottii*), many of which are 50 cm diameter at breast height or larger. Large trees in the Swift Track may have been spared from logging efforts because Mobile Bay to the west and dense swamp vegetation to the east make logging operations particularly difficult. The regional climate of the Weeks Bay area is characterized by moderate winters, hot summers, and abundant precipitation. January temperatures average 10°C, July temperatures average 28°C, and annual precipitation averages 1700 mm (COASTAL WEATHER RESEARCH CENTER, 2005).

METHODOLOGY

Tropical Cyclone Database

The first step in proving or disproving these hypotheses is the construction of a tropical cyclone database for the Weeks Bay area. The database was constructed from archival tropical cyclone tracks as available from the NATIONAL HURRICANE CENTER AND TROPICAL PREDICTION CENTER (2005) and UNISYS WEATHER (2005) web servers. Tropical storms and hurricanes that came within 80.5 km (50 mi) of Mobile Bay between 1850 and 1999 were noted and included in the database. The 80.5 km distance was used as a cut off because the average tropical cyclone diameter ranges from 161 km to 966 km (BARRY and CHORLEY, 1997); thus, the 80.5 km limit would include those storms where the eye wall, the most intense part of the storm, passed close to the study site. The daily latitude and longitude coordinates of these cyclone tracks were plotted with geographic information system (GIS) software. Line maps that showed the position of the storm and its corresponding intensity (tropical depression, tropical storm, or hurricane) were digitized over cyclone track coordinates. From these maps, we were able to determine the proximity of each tropical cyclone to the study site, the day of landfall, and the wind speed of the storm when it either made landfall or was closest to the study site.

Tree-Ring Field and Laboratory Methodology

To assess tree-ring growth, slash pine trees were sampled from the Swift Track area of the Weeks Bay NERR during November 1999 and January 2000. We traversed the area and identified the largest and hopefully the oldest slash pines for coring. Increment core samples were collected from 36 trees at 30 cm above the ground using standard coring methodology (PHIPPS, 1985). Two cores were collected from each tree at 90° angles to account for rings that may not have been continuous around the trunk. All cores were glued into wooden core mounts and sanded according to standard procedures outlined by PHIPPS (1985) and STOKES and SMILEY (1968). Rings from each core were measured to the nearest 0.01 mm using the Unislide "TA" Tree-Ring Measurement System and Measure J2X software (VELMEX, INC., 2005).

The raw tree-ring measurements were cross-dated using the software program COFECHA (HOLMES, 1986). Cross-dating is a technique that improves data accuracy by identifying false rings, missing rings, and double rings within each of the cores. COFECHA works by comparing 50 y segments from each core to the master chronology. It then identifies those rings that substantially deviate (3.0 standard deviations above the mean or 4.5 standard deviations below the mean) from the sample average for a given year (GRISSINO-MAYER, 1997). The tree-ring record is then adjusted to account for deviant rings.

After the raw ring measurements were cross-dated, a master chronology of the entire stand was produced using the software program ARSTAN (COOK and HOLMES, 1986). Tree-ring widths decrease naturally over time as individual trees age and become less vigorous (FRITTS, 1976; STAHLE and CLEAVELAND, 1992). The software program ARSTAN is used to detrend this variation by fitting a series of negative exponential growth curves to the data. The output from ARSTAN is a single, standardized ring index value for each year that is calculated from all ring measurements within the sample for that same year. The standardized ring index series was computed for every year within the chronology. The master chronology in this study spans the time period from 1872–1999; however the ring indices for years before 1890 were derived from only a few individual trees (less than five). Because these early ring index values were computed from a very low sample size, tree-ring index values before 1890 were excluded from the data analysis.

Data Analysis

To determine if a general tropical cyclone signature was evident within the index series, we first compared the series master chronology to years of known tropical cyclone events that passed within 80.5 km of the study area. Second, we performed nonparametric Wilcoxon Signed-Rank tests of index series widths for 2 to 7 y periods before and after the occurrence of a tropical cyclone. As an example, all index values two years prior to known cyclone strikes were compared against all index values two years after. This was repeated for time periods up to 7 y. The 7 y period was set as a maximum because DOYLE and GORHAM (1996) had found growth suppression in the tree-ring chronology up to 7 y after Hurricane Camille. A nonparametric test was chosen due to the relatively small sample size (20 tropical cyclones) and the potential nonnormality of the data (BURT and BARBER, 1996).The null hypothesis for each test was that there would be no statistically significant difference in the median and mean series width values before and after a tropical storm or hurricane. Each test was completed at the 95% confidence interval.

The relationship between the strength of a tropical cyclone and the change in index series before and after a tropical cyclone was assessed by linear regression. Differences in the index series before and after each cyclone were modeled as a function of wind speeds at the location closest to the study area. Wind speeds at the most proximal distance to the study site were determined from the GIS maps described earlier. The regression analysis was completed for each of the 1 through 7 y periods. The reason for this step was to further refine analysis of the potential relationship between tropical cyclone and forests by testing a common assumption that the more intense the tropical cyclone, the larger the impact upon the coastal forest and vice versa.

The second hypothesis was tested through correlation and regression analyses. Spearman rank correlation analysis was used to identify the climate variables that were most strongly related to the index series (temperature, precipitation, and Palmer Drought Severity Index). Climate data for Alabama Climate Division 8 was taken from The National Climatic Data Center (www.ncdc.noaa.gov) and used in this analysis. The earliest year of climate data is 1896, and thus all statistical analyses of tree-ring data and climate data used the 1896 to 1999 time period. The most highly correlated climate variables were then used to construct lag and cumulative climatic variables that were correlated with the index series. The reason for the inclusion of the lag and cumulative variables in analysis was to account for potential lagged growth response of trees. For example, a severe drought in late fall may be evidenced within the tree ring of the following year, and thus analysis of present-year variables alone would not identify such a lag or cumulative relationship.

Once we identified the climate variables most strongly correlated to the index series, we used linear regression to model the index values as a function of climate. Accordingly, the residuals from this regression model represent variation in the tree-ring chronology that was not related to regional climate variables. We believe that a tropical cyclone response in the index series may be evidenced as a large negative residual from a regression model of either precipitation or drought. In this case, the model would predict wider rings with a high amount of moisture. However, the growth rings would actually be smaller than expected due to damage from the tropical cyclone. We would expect to see evidence of a tropical cyclone signal by comparing the standardized residuals to years of known tropical cyclone strikes. In addition, an examination of leverage values from this regression model should also help elucidate a possible tropical cyclone signature. Leverage values are defined as the most influential data points on the regression model (ANDERSON *et al.*, 1983). High leverage values from a regression of tree-ring data and precipitation may represent extremely anomalous years, which might be attributed to tropical cyclones.

The final step in our data analysis was to test our third hypothesis concerning tree-ring signals at the individual tree scale. This involved identifying years in which trees within the study show substantial increases in growth (release years) or suppressed growth (suppression years). This analysis was performed on the standardized tree level indices (option 11 from ARSTAN), which represent detrended index values calculated for each individual tree core series. Within each sample, starting at the sixth annual ring, we computed the average index values of the five previous years and the average index values of the next five years. Next, we computed a ratio of these two averages by dividing the future year's average index values by the past year's average index values. This procedure was repeated for every ring within the chronology. Definitions of a release year and a suppression year were based on and modified from other dendrochronological research (CANHAM, 1985; CAO and OHKUBO, 1999; DOYLE and GORHAM, 1996; LORIMER *et al.,* 1999). Specifically, a release is defined as a 200% increase in growth over the five year interval (DOYLE and GORHAM, 1996). Suppression years were calculated in a similar manner but are defined as a 50% decrease in growth over the five year interval. From these ratios, we determined the percentage of trees showing release or suppression for each year. The occurrence of release or suppression years was then compared to the tropical cyclone database to determine if potential relationships existed between tropical cyclone and tree release and suppression.

Table 1. *Hurricanes and tropical storms making landfall within 80.5 km of Mobile, Alabama, 1850–1998. The storm type is based on the maximum category obtained during the storm path within the Gulf of Mexico. Wind speeds are reported for the time at landfall or for the closest geographic position to the study site. Data are derived from UNYSIS Weather (2005); all dates are 2005.*

Year	Date	Maximum Storm Type in Gulf	Estimated Wind Speed (km/h)	Name
1852	19–27 August	Category 3	185.1	Not named
1859	16 September	Category 1	148.1	Not named
1860	8–16 August	Category 3	128.7	Not named
1870	30 July	Category 1	128.7	Not named
1877	14–21 September	Category 1	128.7	Not named
1881	1–4 August	Tropical Storm	91.7	Not named
1882	2–13 September	Category 3	185.1	Not named
1885	24 Sept.–2 Oct.	Category 1	110.0	Not named
1887	9–19 October	Category 2	64.4	Not named
1889	11–26 September	Category 2	112.7	Not named
1893	27 Sept.–5 Oct.	Category 2	138.4	Not named
1901	10–14 June	Tropical Storm	64.4	Not named
1902	3–13 October	Category 2	91.7	Not named
1904	29 Oct.–5 Nov	Tropical Storm	64.4	Not named
1906	19–29 September	Category 4	212.4	Not named
1911	9–14 August	Category 1	128.7	Not named
1912	11–14 September	Category 1	128.7	Not named
1914	14–19 September	Tropical Storm	64.4	Not named
1916	12–19 October	Category 3	185.1	Not named
1922	12–17 October	Tropical Storm	72.4	Not named
1926	11–22 September	Category 4	185.1	Not named
1932	26 Aug.–4 Sept.	Category 1	128.7	Not named
1934	1–6 October	Tropical Storm	64.4	Not named
1936	27 July–1 Aug.	Category 1	120.7	Not named
1950	20 Aug.–1 Sept.	Category 2	120.7	Baker
1959	6–9 October	Tropical Storm	91.7	Irene
1979	29 Aug.–15 Sept.	Category 4	177.0	Frederic
1985	28 Aug.–4 Sept.	Category 3	185.1	Elena
1995	31 July–6 Aug.	Category 1	119.1	Erin
1997	16–17 July	Category 1	112.7	Danny
1998	15 Sept.–1 Oct.	Category 2	72.4	Georges

RESULTS

Tropical Cyclone Database

A list of the 31 tropical cyclones that passed within 80.5 km of Mobile Bay is shown in Table 1. The storms that came

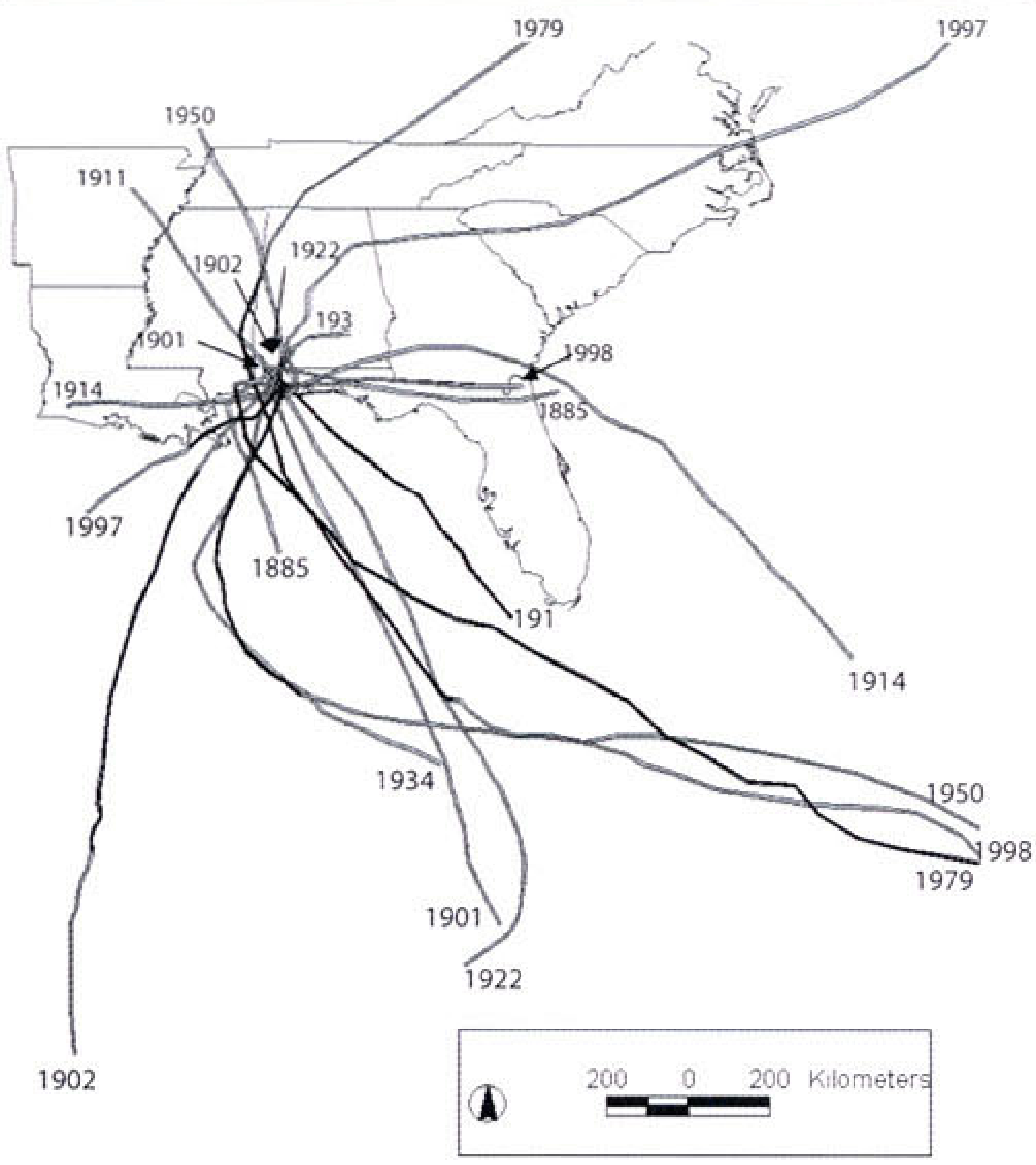

Figure 2. Tropical storm and hurricane tracks during the time period 1881–1998 within 80.5 km of the study area. Black lines represent cyclones at hurricane strength, and gray lines represent cyclones at either tropical depression or tropical storm intensity.

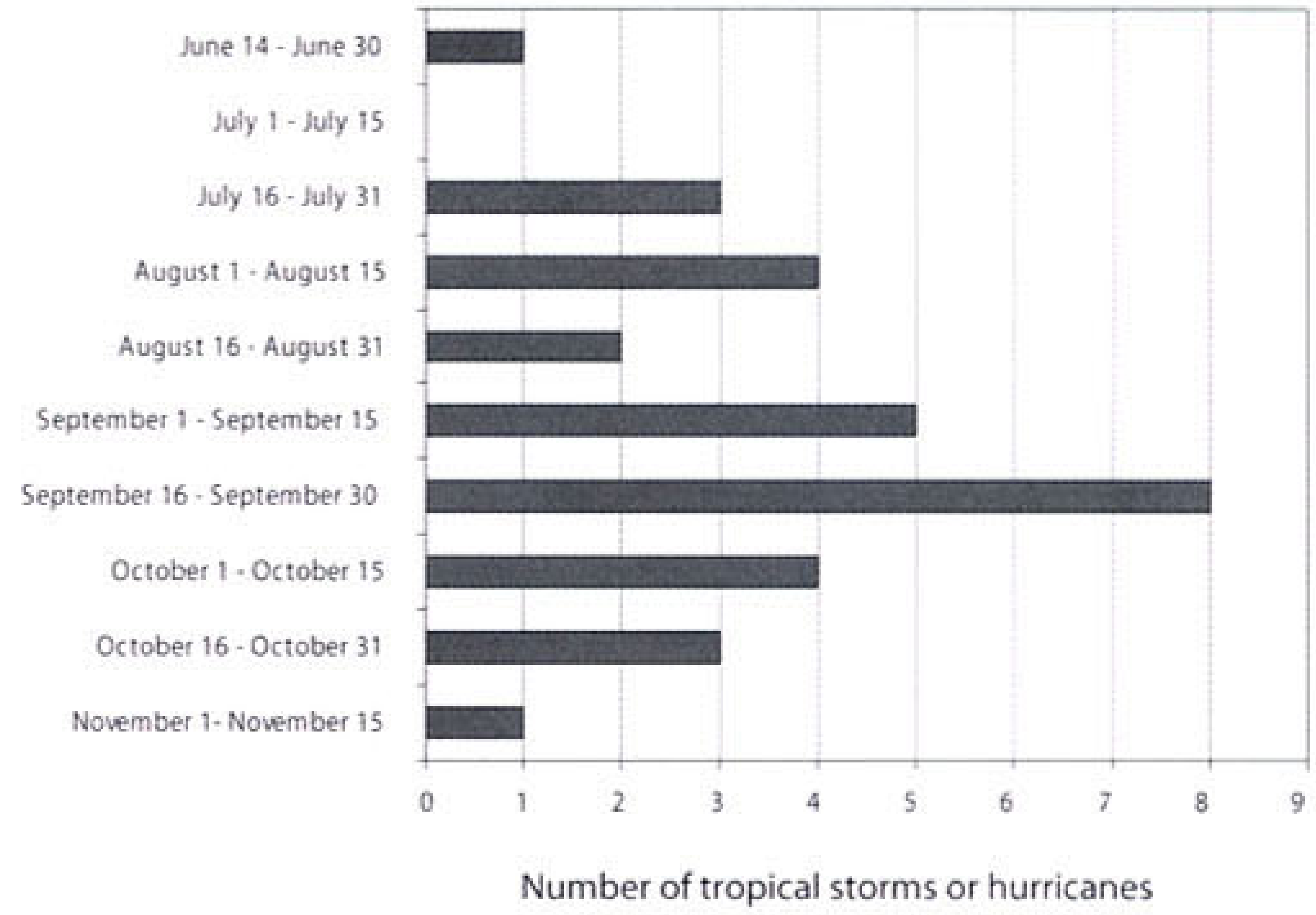

Figure 3. Number of tropical storms and hurricanes making landfall within 80.5 km of Weeks Bay by date from 1888 to 2000.

closest to the Weeks Bay study site include events in 1885, 1901, 1902, 1911, 1914, 1922, 1934, 1950 (Baker), 1979 (Frederic), 1997 (Danny), and 1998 (Georges; Figure 2). The highest category storm that made landfall within 80.5 km of the study site was Baker in 1950. However, once Baker reached the study area, wind speeds were estimated to be only 120.7 km/h. The major hurricanes of 1906, 1916, 1926, 1979 (Frederic), 1985 (Elena), and 1995 (Erin) came within the Weeks Bay vicinity but did not make a direct hit on the study area. These storms had a wide range in intensity, with minimum wind speeds of 64.4 km/h (4 tropical cyclones) and a maximum of 212.4 km/h at landfall (1906 hurricane).

Three periods of tropical cyclone activity are evident from the tropical cyclone database (Table 1). The first period is from 1850 to 1936, a period when tropical cyclone probability for a given year was 0.28. The second period, 1937–1978, represents a period of low tropical frequency with two storms in the 51 y period, or a 0.04 probability of a tropical cyclone for a given year. The final period, 1979–2000, has a 0.24 probability of annual tropical cyclone occurrence. Thus, we believe that the normal annual tropical cyclone probability for the Weeks Bay area is about 0.25, and this probability existed for the majority of the period of record (1850–1936 and 1979–2000).

It is evident from the historical record that the Weeks Bay area is most vulnerable to tropical cyclones during mid-September (Figure 3). No hurricanes and only one storm (1901 tropical storm) were within the vicinity before July 1. No hurricanes and only one tropical storm (1904 tropical storm) occurred after October 31st. The relevance of this monthly frequency to the current study is that tropical cyclones and hurricanes that either made landfall or came close to the study site did so during the late summer and early fall months. This is within the active growing season of slash pine. Therefore, it is believed that the effects of a hurricane should be evident within the tree-ring data either within that same year or immediately thereafter.

Standardized Ring Index Series

The results of the COFECHA cross-dating were successful in producing a series intercorrelation of 0.371 and an average mean sensitivity of 0.358. The index series master chronology indicates a noticeable decline from the 1890s to about 1911 (Figure 4). This period was followed by a period of increase in the series until 1937. Next, a decline in series occurred until 1981, followed by an increase to the series' highest val-

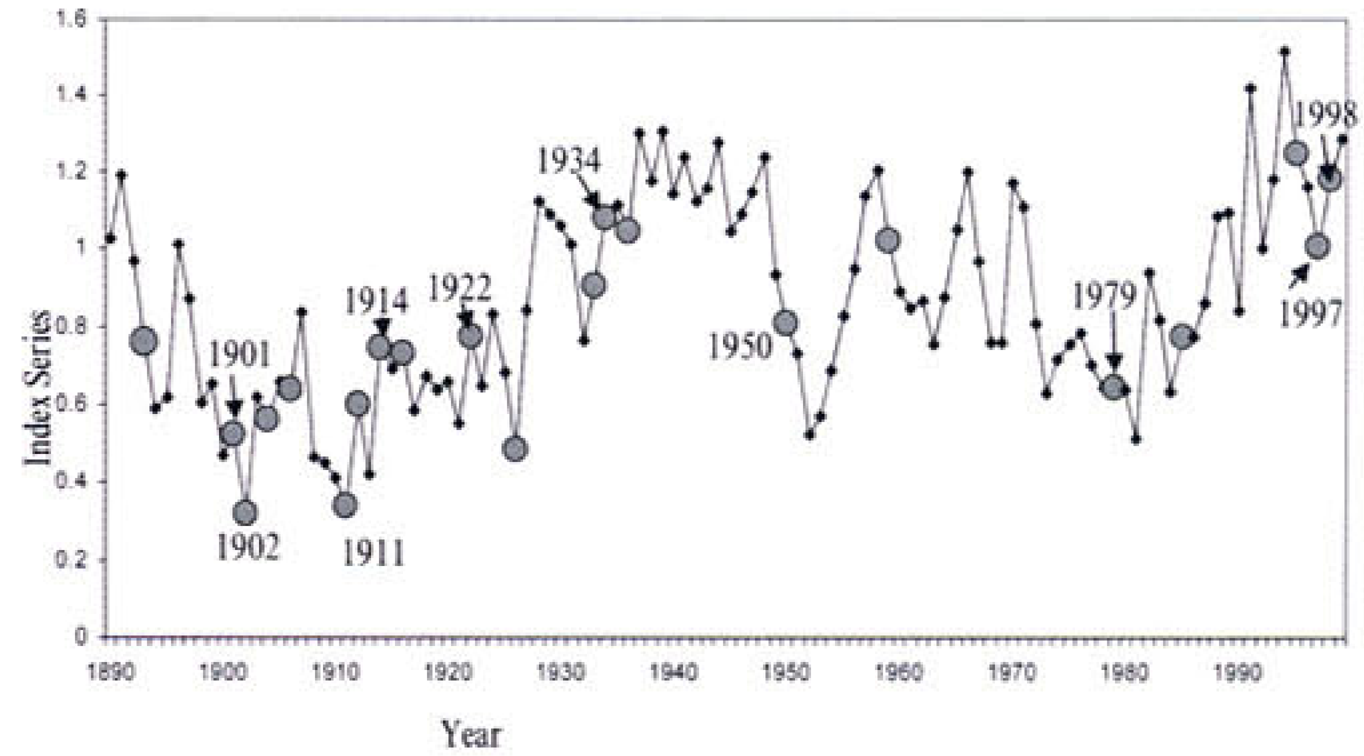

Figure 4. Standardized ring index series (master chronology) of the Swift Track trees for each year from 1890 to 2000. Years with tropical cyclone strikes within 80.5 km of the study area are labeled on the graph and noted with large gray circles.

ues at the end of the period of record. Short-term oscillations between increase and decrease in the index series are superimposed over this general sinusoidal pattern, suggesting a potential random component to this time series. The negative exponential detrending curve produced from ARSTAN was lower than the unstandardized ring width series for years 1950–1999. This indicates that the index series has slightly inflated values toward the latter half of the twentieth century.

The Index Series and Tropical Cyclones

A visual examination of the index series and years of known tropical cyclone strikes offers no clear pattern of tree-ring response to tropical storms or hurricanes. Tropical storms and hurricanes occur during both upward and downward trends across multiple time scales in the time series. As mentioned previously, the tropical cyclones of 1901, 1902, 1911, 1914, 1922, 1934, 1950, 1979, 1997, and 1998 came closest to the site and thus may have had the greatest impact on the study site. The 1901 and 1902 cyclones had wind speeds of 64.4 and 91.7 km/h, respectively, at the time they made landfall, and came very close to study area. The index values for these years are some of the lowest of the entire record (Figure 4). The 1911 hurricane came ashore very close to the study site, with wind speeds estimated at 128.7 km/h. The index value for 1911 is very low, similar to that of 1901 and 1902, suggesting perhaps that tropical cyclones produce low index values. However, the tropical storms of 1914, 1922, and 1934 made landfall very close to the study site, but the index values are much higher and, in contrast to the above, they are part of an overall increase in index values. Hurricane Baker in 1950 was perhaps the largest tropical cyclone (in terms of area) making landfall within the study site over the last 150 y, but its winds were only 120.7 km/h (about average in this data set). The index series before 1950 indicates that the overall growth trend was already in decline. After 1950, however, index values drop precipitously to the lowest values of the middle and late twentieth century. Hurricane Frederic (1979) probably had the greatest effect on the city of Mobile (Coastal Weather Research Center, 2005) in the twentieth century; however, it made landfall on the opposite side of the bay from the study site. The index series shows no major fluctuations either during or immediately after 1979, but the values drop soon after Frederic to the lowest levels of the middle and late twentieth century. Hurricane Danny (1997) made a direct hit on the study area. When Danny came ashore, it had estimated wind speeds of 112.7 km/h and stalled over the study area for several days, generating record amounts of rainfall. The overall series trend for the mid-1990s was already declining, yet the 1997 value was the lowest from 1991–1999. Hurricane Georges (1998) rapidly decreased in intensity after making landfall near the study area. It was downgraded to a tropical depression with wind speeds estimated at only 72.4 km/h. There is no major fluctuation in the master chronology during or after 1998; in fact, the index series continues to increase. Thus, a clear relationship between individual tropical cyclone events passing close to the study area and a time series of the stand-scale index series cannot be ascertained though a visual comparison. Of the 11 tropical cyclones to come closest to the study site, it appears only 6 storms (1901, 1902, 1911, Baker, Frederic, and Danny) can be associated with low index values.

Since the index series may also be sensitive to the frequency of storms within the general vicinity and not to just storms making landfall nearby, we examined the frequency of storms per decade with relation to the index series. As mentioned, during the 1880s, there were five storms, the greatest decadal frequency on record. The 1900s and 1910s were also active with four storms per decade. The middle and later part of the twentieth century was the least active, with only one major storm occurring from the 1930s to middle 1970s (Baker). From the 1979 to 2000, several storms occurred. Two storms in particular, Danny and Georges, occurred back to back. Such results support the three periods in tropical cyclone frequency (normal pre-1937, low 1937–1978, normal post-1978) discussed previously in the results section. However, it is difficult to ascertain a relationship between the index series and this tropical cyclone frequency (Figure 4). Two different patterns in the series exist during the periods of normal tropical cyclone activity—a decrease and increase in the pre-1937 period and an increase in the post-1978 period. Thus, a clear association does not exist between tropical cyclone frequency and tree stand index series.

Wilcoxon Signed-Rank Test and Linear Regression Analysis

The Wilcoxon Ranked-Signs Tests indicate that the median of the mean index series values for the 2 through 7 y periods before and after a tropical cyclone in the Weeks Bay NERR are not significantly different at the 95% confidence interval. Further, linear regression analysis indicates that wind speed of the tropical cyclone at landfall is a poor predictor of the change in index values before and after a tropical cyclone for each of the 2 to 7 y periods, because none of the linear models possessing an r^2 value greater than 0.03.

The Index Series and Climate Variables

The next step in this analysis was to use correlation and regression analyses to remove background climatic noise, which may mask potential tropical cyclone signals. These statistical analyses may also help refine possible relationships between the tree-stand-scale series and tropical cyclones. First, we correlated the index series with seasonal and annual climate precipitation, temperature, and Palmer Drought Severity Index (PDSI; Table 2). In terms of precipitation, annual precipitation has the highest significant correlation with the index series ($r = 0.384$), followed by spring and summer precipitation ($r = 0.305$ and 0.230, respectively). This result, even though correlation coefficients are low, suggests that a wet year caused by high rain in spring and summer is associated with an increase in the series, or tree growth. All seasons and annual PDSI showed significant correlations with index values, and the strongest associations were in summer ($r = 0.383$) and fall ($r = 0.356$; Table 2). This implies that drought conditions, particularly in summer and fall, are related to tree growth. Only summer temperatures were sig-

Table 2. *Spearman Rank Correlation analysis of index series and climate variables of the current year, index series and climate variables lagged one year, and index series and climate variables cumulative of the previous year and current year.* * = *significant at* $p < 0.05$.

Climate Variable	Current Year	One Year Lag	Cumulative of Previous Year and Current Year
Drought (PDSI)			
Annual	0.357*	0.332*	0.424*
Winter	0.290*	0.224*	0.348*
Spring	0.271*	0.298*	0.338*
Summer	0.383*	0.337*	0.451*
Fall	0.356*	0.279*	0.424*
Precipitation			
Annual	0.384*	0.326*	0.456*
Winter	0.009	0.00	−0.06
Spring	0.305*	0.220*	0.320*
Summer	0.230*	0.289*	0.349*
Fall	0.180	0.112	0.202*
Temperature			
Annual	−0.069		
Winter	0.081		
Spring	−0.056		
Summer	−0.205*		
Fall	−0.132		

nificantly correlated to the index series, but the coefficient represents weak association. Even though summer temperatures do not have a large influence upon index values, the significant correlation does support the drought index results. Higher temperatures will decrease soil moisture in the summer, which leads to decreased tree-ring width.

A cumulative impact of climate on tree growth was also assessed through the combination of the current year and the previous year's climate (Table 2). This combination of present and past data increased the correlation coefficients. Average annual precipitation had the highest correlation ($r = 0.456$), followed by average summer PDSI ($r = 0.424$) and average annual PDSI ($r = 0.424$). These results further support the

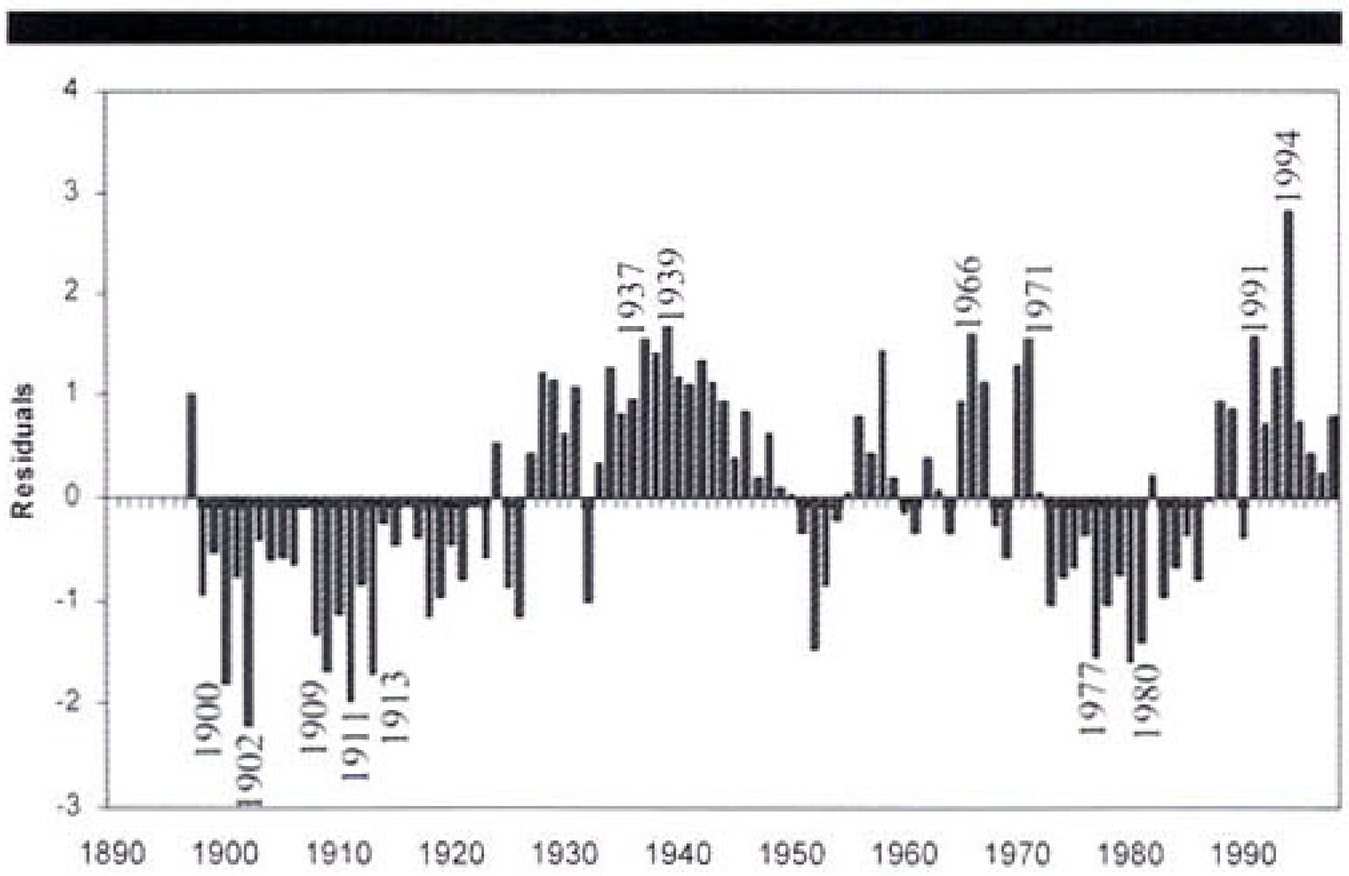

Figure 5. Residuals from a linear regression of standardized ring index series and precipitation. Precipitation values represent the average of the current year annual precipitation and the annual precipitation lagged by one year. Years with the lowest residuals (<−1.55) and highest residuals (>+1.55) are labeled on the graph.

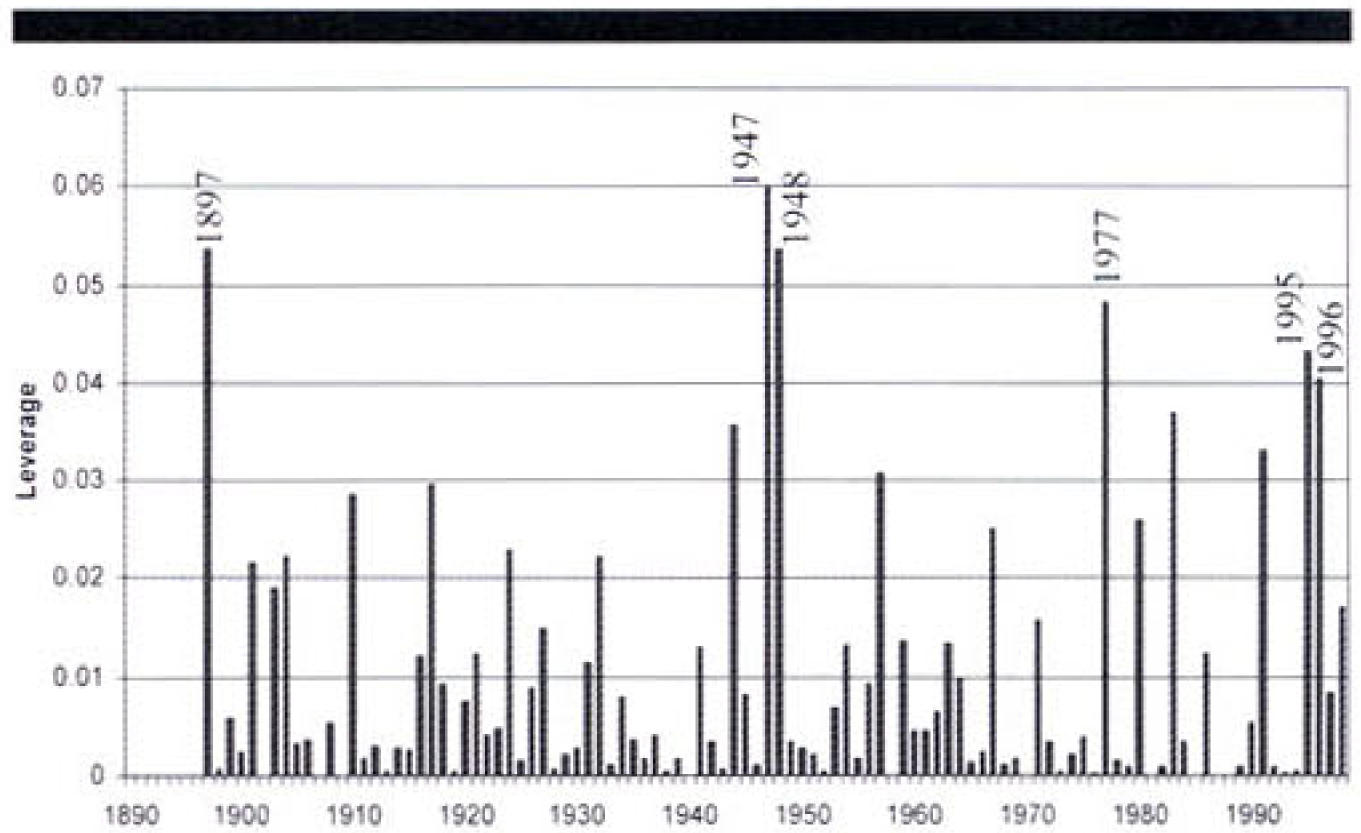

Figure 6. Leverage values form linear regression of standardized ring index and precipitation. Precipitation values represent average of the current year annual precipitation and the annual precipitation lagged by one year. Years with the six highest leverage values are labeled on the graph.

hypothesis that high moisture, particularly in summer and fall, is associated with tree growth. Additionally, a high amount of rain in a given year, created by a wet spring and summer, is also associated with tree growth.

The next step in the analysis was to complete a linear regression to model the index series as a function of climate. We used the average annual precipitation of current year and previous year as the independent climate variable because it had the highest correlation. The regression was significant ($p = 0.001$), but the r^2 was weak ($r^2 = 0.20$). The residuals of the regression model represent the variation in tree growth that is not related to precipitation (Figure 5). Our hypothesis is that a large negative residual might be indicative of a hurricane signal because the model would greatly overestimate the tree growth given a high amount of precipitation. This is because a year with a hurricane would likely have a normal to high amount of annual precipitation, yet damage from the hurricane would make the ring index smaller. Thus, a large negative residual would be high precipitation (possibly from hurricane) and lower-than-expected growth (from hurricane damage). Most of the large negative residuals do not coincide with years of known hurricane strikes. With the exception of 1902 and 1911, the remaining lowest residuals (1900, 1909, 1913, 1977, and 1980) did not occur during hurricane years; thus, a relationship is not apparent. Large positive residuals indicate years when the regression model underestimated tree growth. The largest positive residuals occur in years 1937, 1939, 1966, 1971, 1991, and 1994. All six residuals happen during periods in which hurricanes were infrequent. Besides examining large negative residuals, we also compared the leverage values from the regression equation to years of known hurricane strikes (Figure 6). As mentioned, leverage values represent the data values that had the most influence on the regression model. With the exception of 1995 (Hurricane Erin), the highest leverage values (1897, 1947, 1948, 1977, and 1996) do not coincide with known cyclone strikes.

Individual Tree Suppression and Release and Tropical Cyclones

Years with high release occur during and directly after active tropical cyclones periods or directly after a direct hit from

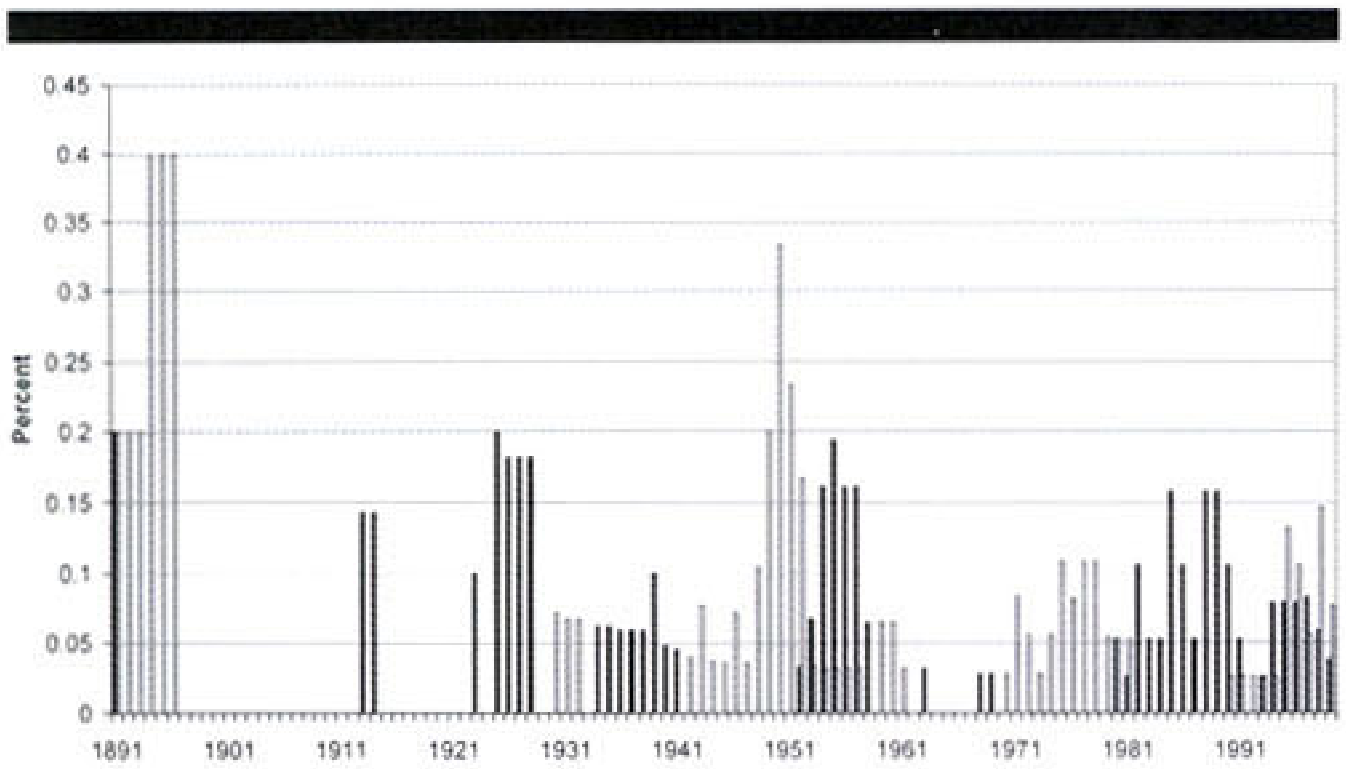

Figure 7. Percent of trees showing release (200% increase in growth over a five year period) or suppression (50% decrease in growth over a five year period) within the Swift Track study area. Black shaded bars show the percent release, and white shaded bars show percent suppression.

one major storm (Figure 7). Suppression years, in contrast, occur after long periods of time when tropical cyclone activity is infrequent. The high release values of the late nineteenth century have little significance because of extremely low sample sizes (only 5 trees in the total). The earliest significant cluster of release years occurs from 1912 to 1913 and from 1920 to 1928. This timing corresponds to a very active tropical cyclone period where there were six storms from 1911 to 1926. It is also worth noting that no suppression years occurred during this time. A second cluster of release years occurs from 1934 to 1941 (Figure 7). This time frame corresponds to an active tropical cyclone period when three storms (1932, 1934, and 1936) made landfall within a four year time frame. Release years did not occur during the 1940s and early 1950s; however, the proportion of trees showing suppression is high. For example, the suppression value for 1950 is the highest of the twentieth century, where a third of all trees (33.3%) showed evidence of suppressed growth. The high suppression values are coincident to the end of a quiet tropical cyclone time period. No significant storms made landfall from 1937 until 1949. This was the second quietest tropical cyclone period of the twentieth century. The quiet tropical cyclone period, though, was interrupted by Hurricane Baker in 1950, which was the most intense storm to directly hit the Weeks Bay area. Following Hurricane Baker, the record shows a switch from high suppression years to high release years (1952–1958).

Clusters of high suppression years once again become evident at 1959–1961 and 1970–1980. This time interval had the lowest tropical cyclone frequency of the twentieth century. Only two storms (1959 and 1979) made landfall within the Weeks Bay area from 1951 to 1985. After 1980, though, the pattern switches from suppression to release. The timing of this change coincides with the landfall of Hurricane Frederic in 1979.

Release and suppression are mixed during the later twentieth century (1990–2000). This mixed signal may represent a transition from a quiet to active tropical cyclone period with suppression values slightly greater than release values from 1996. This may be related to the five storms making landfall near the Weeks Bay area from 1979 to 1998, in particular, tropical cyclones Hurricane Danny (1997) and Hurricane Georges (1998) that directly hit the Swift Track study area.

DISCUSSION

A visual examination of the index series for the Swift Track indicates that years of known tropical storms and hurricane landfalls do not coincide with major changes in tree growth when examined at the stand scale. A statistical analysis of the index series for Weeks Bay area does not indicate a statistically significant difference in median index values for 2 to 7 y periods before and after a hurricane. Thus, our first hypothesis was not supported by the data, indicating that other physical and biological processes related to tree growth mask damage sustained from tropical cyclones at the stand level. One possible reason for the absence of a stand-scale signal is that all trees that were used to construct the chronology were from those that actually survived the tropical cyclones. The trees that succumbed to the effects of the storm were not represented. The surviving individuals, then, may have been more resistant individuals or they may have been located in areas that were more sheltered from high winds and standing floods. In our research design, we made the assumption that because there was little topographic variation and most of the trees were located only a hundred meters or so from the shore, any damage from a tropical cyclone would be widespread and dispersed across the entire stand. However, the surviving trees may have been afforded more protection within certain microhabitats. A comparison of surviving trees to those that died as a result of the storm damage may prove more useful in elucidating a tropical cyclone signal.

Analysis of the link between general climate conditions and the tree-ring chronology indicates that the tree-ring record is sensitive to climactic variation, especially to moisture levels. At least twenty percent of the growth of the stand is associated with cumulative rainfall from one growing season to the next. Alabama Climate Division 8 is one of the wettest areas in the continental United States. Even though significant moisture is usually available throughout the year, and the area is predominately wet, it is interesting to note that slash pine growth in Weeks Bay area still shows a significant relationship to precipitation. A significant portion of the variability in tree-ring chronology, however, is yet to be explained (80%). Because a small amount of the variability in tree growth is related to climate, it is not surprising that the residuals or leverage values from the linear regression model did not improve our detection of a tropical cyclone signal. Thus, our second hypothesis did not hold true. Continuing research is needed to determine the remaining physical and biological factors that are most strongly related to the tree-ring pattern from our study site.

The effects of tropical cyclones are evident within the standardized tree index values of individual trees. Release years (200% average increase in growth over a five year period) occur following seasons when tropical cyclone activity is high. Examples include the high release values of the 1920s, 1930s, and 1980–1990s. Furthermore, high release values are associated with the landfall of just one major storm. The high release values of the early 1950s and early 1980s, for example, coincide with the landfall of Hurricanes Baker and Frederic, respectively. Suppression years (50% decline in growth over a five year period), in contrast, typically occur within prolonged periods of inactive tropical cyclones. This is evidenced by the high suppression values of the 1940s and early 1970s, which were periods in which tropical cyclone probabilities were exceptionally low (one storm within 10+ y). However, it should be noted that tree-ring analysis is only limited to a small portion of the forest (10%–40%), and this cannot be construed as a stand-wide pattern.

The association between individual tree release and stand-level suppression is possibly related to the disturbance from the tropical cyclones. The stripping of leaves and limbs from dominants and the removal of weaker individuals would potentially open gaps in the forest canopy (RUNKLE, 1981). These gaps would allow more light to reach some of the surviving trees, consequently boosting their growth potential. During periods when tropical cyclones are infrequent, dominant trees would restrict the growth of other individuals in the stand. It would not be until the landfall of another tropical cyclone (such as after Hurricane Baker) and the subsequent opening of the canopy that tree growth would change from suppression to release. This pattern supports the intermediate disturbance hypothesis (CONNELL, 1978), which proposes that higher community diversity is associated with moderate levels of disturbance. The regression analysis of the index series and wind speed of tropical cyclones also support the existence of release in the tree-ring chronology after tropical cyclone occurrence in the Weeks Bay NERR. Even though none of the regressions explained a large amount of variance in the index series or was statistically significant, all regression slopes were positive except for the 2 y period. A positive slope suggests that the higher the wind speed, the greater the index value, or in other words, once a strong tropical cyclone hits the study area, trees are cleared out, and the surviving trees grow, increasing index values.

Given the subtle relationship suggested by the coeval release and suppression of tree rings and tropical cyclone activity, damage from storms is not the only possible explanation for this variation in tree-ring widths in Weeks Bay NERR. For example, research has shown that tree growth in coastal forests of the southeastern United States is impacted by fluctuations in sea level (WILLIAMS *et al.*, 2003), and the combination of hurricanes and fire (MYERS and VAN LEAR, 1998). In addition, the high release values in Weeks Bay during 1998 may have been related to a prescribed burn that occurred in this area during this time. There is also a danger in interpreting the results of raw tree-ring measurements because it is difficult to sort out multiple factors affecting tree growth. However, we believe that the occurrence of both individual tree release and stand-scale suppression is consistent with tropical cyclone activity throughout the twentieth century, underscoring the importance of multiscale analysis in understanding forest ecology in the central Gulf Coast region.

CONCLUSIONS

A tree-ring analysis was completed on the Swift Track forest in the Weeks Bay NERR in order to assess the relationship between hurricanes and coastal slash pine forests. Analysis did not support two tree stand–scale hypotheses. Specifically, direct comparison of a stand-scale index series to tropical cyclone occurrence indicated no obvious relationship between specific hurricanes and tree growth in the coastal forest, and a statistical analysis indicated that tree-ring growth was not statistically different for 2 to 7 y periods before and after a tropical cyclone. Further, statistical analysis (correlation and regression) of monthly climatic conditions indicated a weak association between tropical cyclones and tree stand growth. The highest correlation values exist for annual, spring and summer precipitation, and annual, summer and fall drought. Of these variables, tropical cyclones can be linked to annual precipitation, annual drought, and fall drought. However, these results more likely suggest that rain in the months preceding peak hurricane season, April–August, has a more profound impact upon the forest than tropical cyclones. A third hypothesis related to individual tree growth and tropical cyclones was not supported by this analysis. Instead, a relationship opposite of the hypothesized impact of hurricanes upon individual tree-ring data was suggested by analysis, which indicated a record of growth as opposed to suppression. Specifically, analysis indicated that tree-ring release occurs after tropical cyclones for a small portion of the coastal forest. We believe this is due to the clearing out of weak trees and other debris, allowing some trees to fill open spaces. We believe that the results from this study indicate that researchers must be aware of the scale at which tree-ring analysis of coastal forests is completed. In this study, a combination of results from tree stand– and individual tree–scale analysis resulted in a more complete characterization of overall suppression in a forest with growth for a minority of opportunistic trees after a hurricane. Without testing the hypotheses at multiple scales, a conclusion of only tree growth suppression may have been reached, mischaracterizing the relationship between tropical cyclones and coastal forests in the central Gulf Coast of the United States.

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